Main Injector HLRF Station Gain Measurements

T.Berenc
6/30/2005

Abstract: *Main Injector high-level RF (HLRF) station gain measurements across a large portion of the operational parameter space were made during the HLRF solid-state driver upgrade and mid-level RF (MRF) project. The results of these measurements are documented here.*

Introduction

During the Main Injector (MI) high-level RF (HLRF) solid-state driver (SSD) upgrade of 2004 and the MI mid-level RF (MRF) project of 2005, gain measurements of a typical HLRF station were made as a function of frequency, power amplifier (PA) grid bias, PA anode bias, and RF drive level. The measurements were made at the MI-60 test station. These measurements were used to specify the design of the Station RF Controller module and to understand system scaling factors needed for the MRF design. The Station RF Controller essentially provides the correct RF drive level to the SSD amplifiers in order to achieve a specified user requested cavity voltage. It also processes the Direct RF feedback (FB) and the RF feed-forward (FF) signals used for beam loading compensation. The HLRF station gain measurements documented here were crucial for choosing the components for the Station RF Controller and for understanding HLRF station operation over a large portion of the typical operating parameter space.

There were essentially 3 stages during which the measurements were made:

1. During Station RF Controller module prototyping with 4 SSD amplifiers
   - A complete 8 SSD amplifier rack had not yet been built up at this time; thus a configuration of only 4 SSD amplifiers was used. These measurements were used for initial characterization but did not include the additional scaling that would be introduced by the cathode impedance mismatch when 8 SSD driver amplifiers were finally used. These measurements are still useful for comparison and for determining relative changes in system gain as a function of a parameter.
2. During the final Station RF Controller design with all 8 SSD amplifiers
   - At this time, a complete 8 SSD amplifier rack was available and the Station RF Controller was in its final design phase. Included in these measurements is the cathode voltage standing wave ratio (VSWR) as a function of grid bias.
3. During the MRF development
   - At this time, the results of previous measurements were confirmed and simple measurements were taken at the extremes of the parameter space in order to understand the range in the system gain.

Measurements during Station RF Controller Prototyping

A block diagram of the measurement setup used during the Station RF Controller module prototyping stage is shown in Fig. 1 on the following page. The block diagram shows 4 of the SSD amplifiers crossed out as well as a splitter in the Station RF Controller output. This correctly depicts the fact that only 4 SSD amplifiers were used in the test setup. For these measurements, and for the measurements of the other sections, the system gain was measured from the output of the "RF Switch" at the final output of the Station RF Controller to the cavity gap.

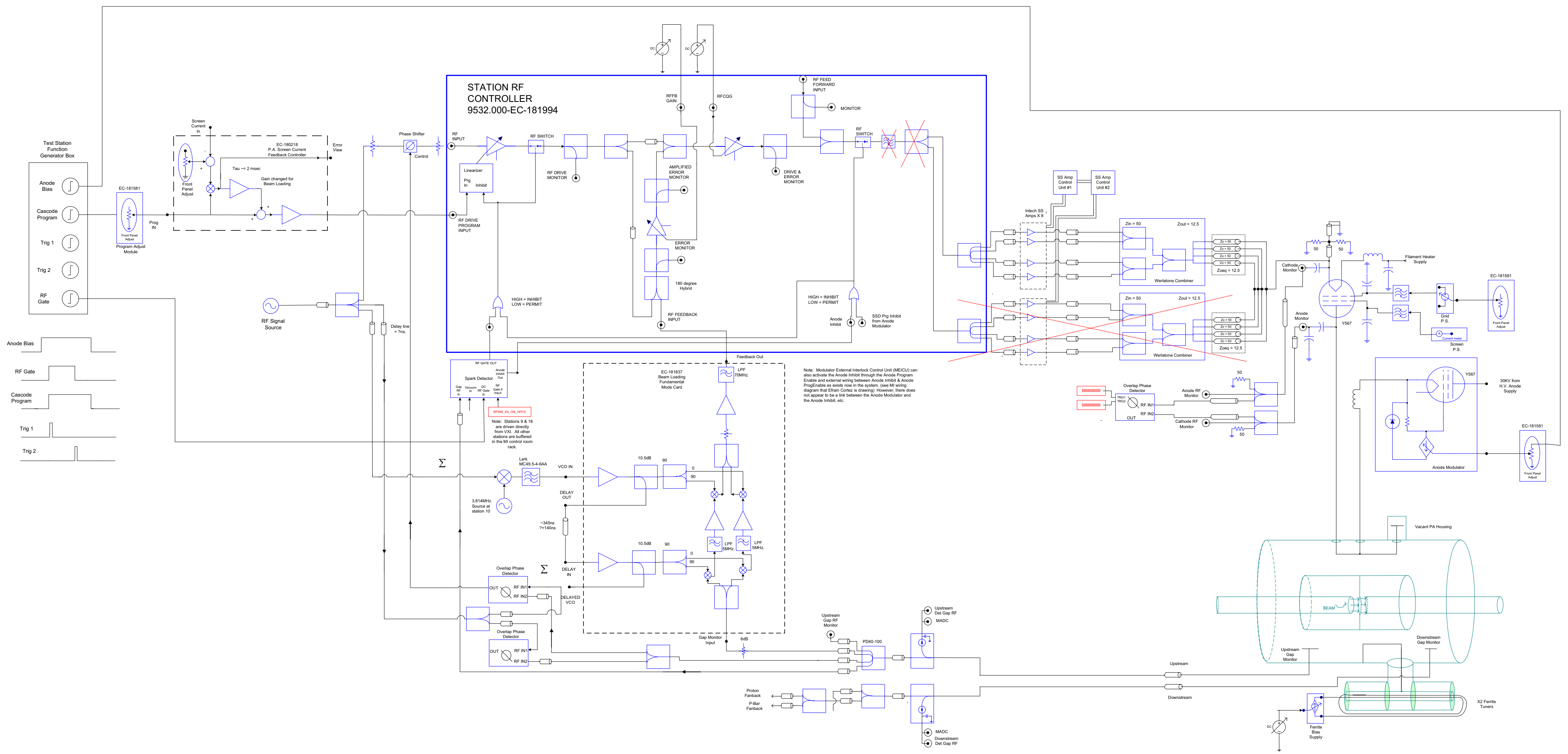
Included in this section are the results of 5 variations on the measurements:

- vs. Frequency
  - note the use of RFOLG to create a constant loop gain
- vs. Grid Bias at 52.814 MHz
  - note the change in anode efficiency vs. grid bias
- vs. Anode Bias at 53.104 MHz
- vs. Drive Level at 52.814 MHz
  - note the gain compression during screen conduction
- vs. Drive Level vs. Frequency
  - simple measurements under no screen current conditions at 3 different frequencies, each at only 2 different drive levels

Note: the calculation of anode efficiency being greater than 100% in the data indicates an error; possibly due to the modulator DC current monitor. It is the change in efficiency over the parameter space that is more relevant. Different modulators were used between these measurements and the measurements of the following sections due to having to support operational modulator replacements; thus one cannot compare absolute values for efficiency.

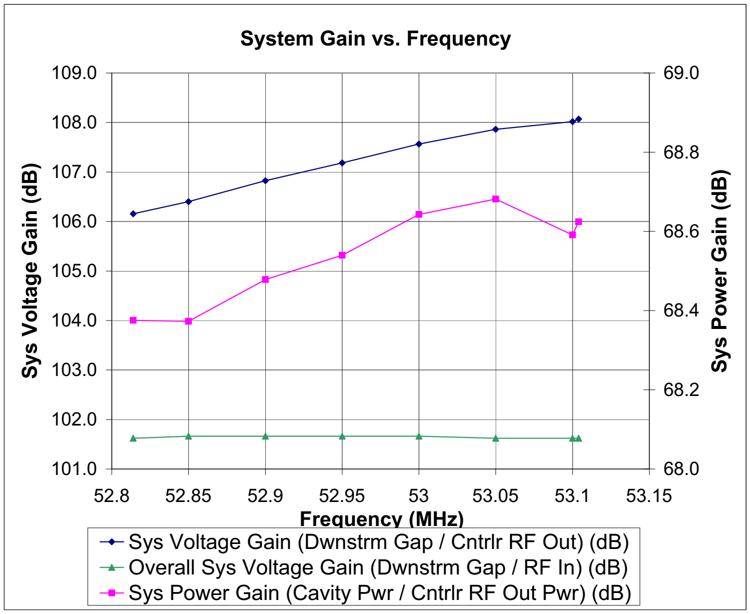
Figure 1

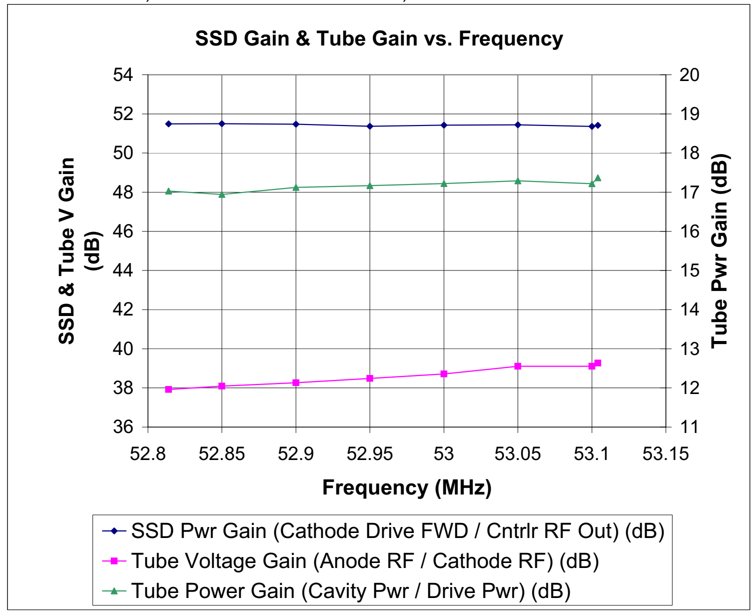
Test Station Block Diagram with Prototype Station RF Controller

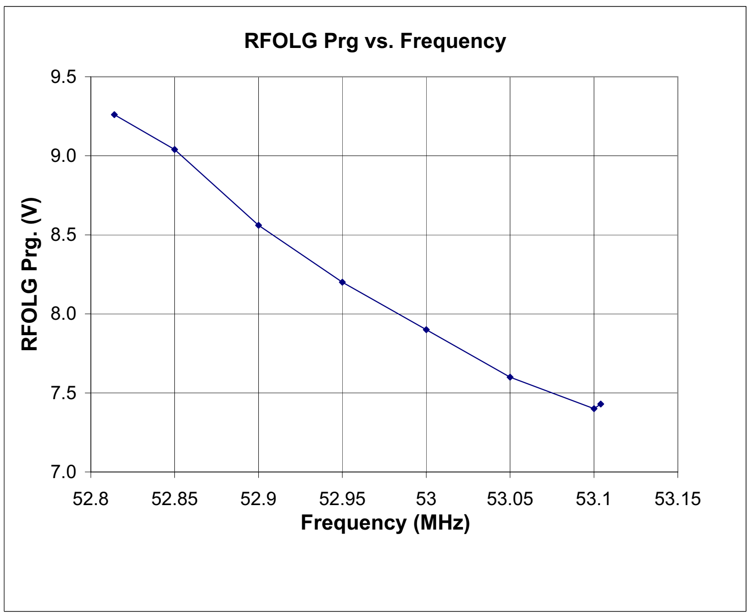


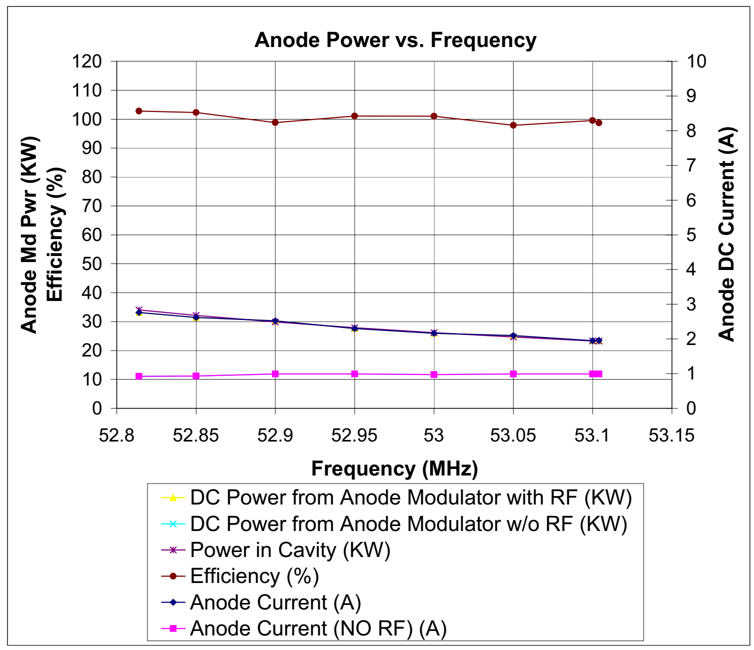
MI Test Station: System Performance vs. Frequency

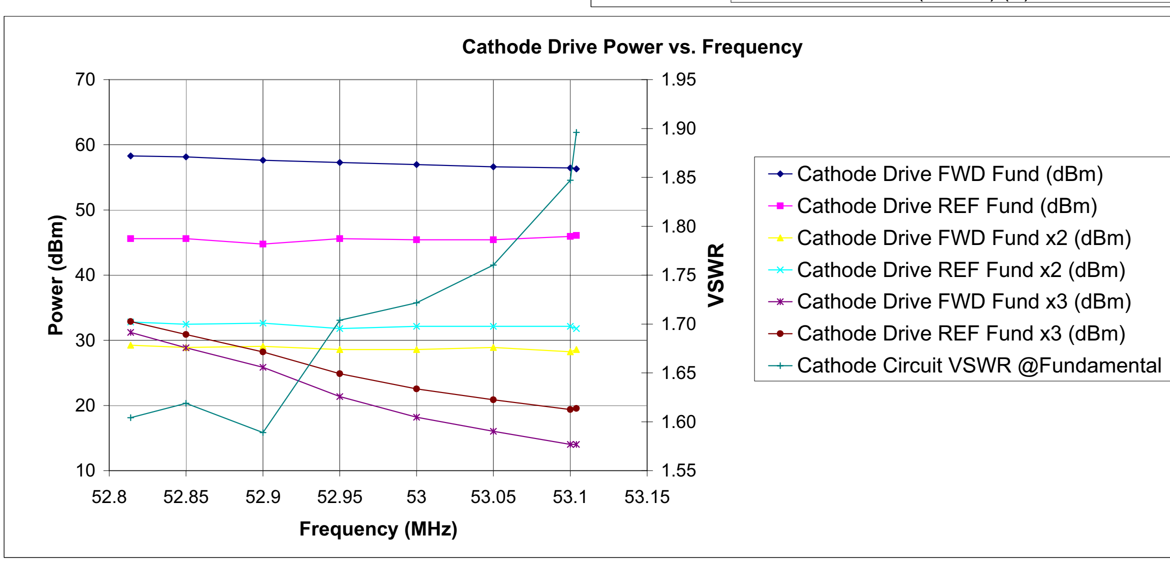
Operating Conditions: Varied the RFOLG Program for fixed voltage gain (Sta RF Cntrlr IN to Gap)
Grid Bias fixed at -292 V, Anode Bias fixed at 12 KV, Screen I at 400 mA







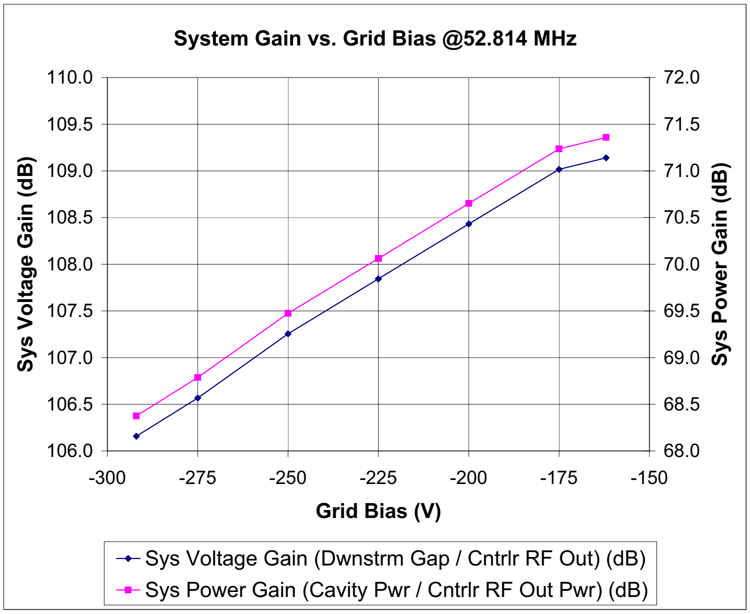


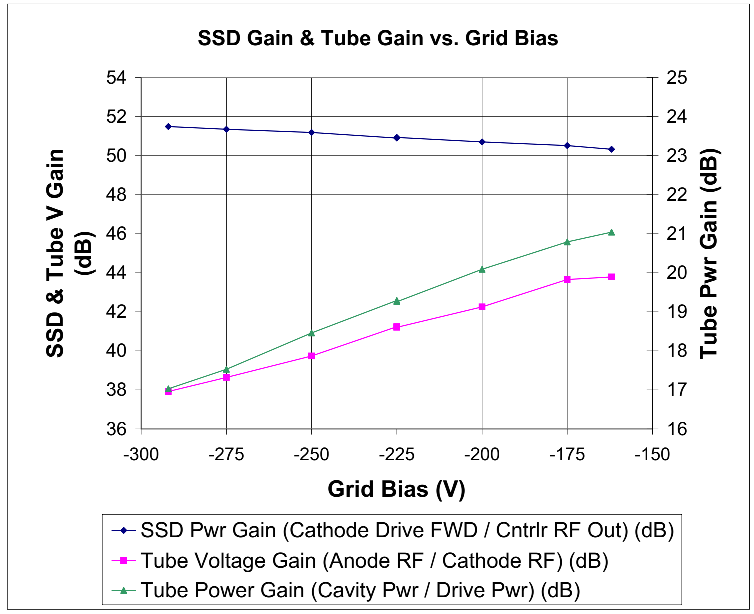


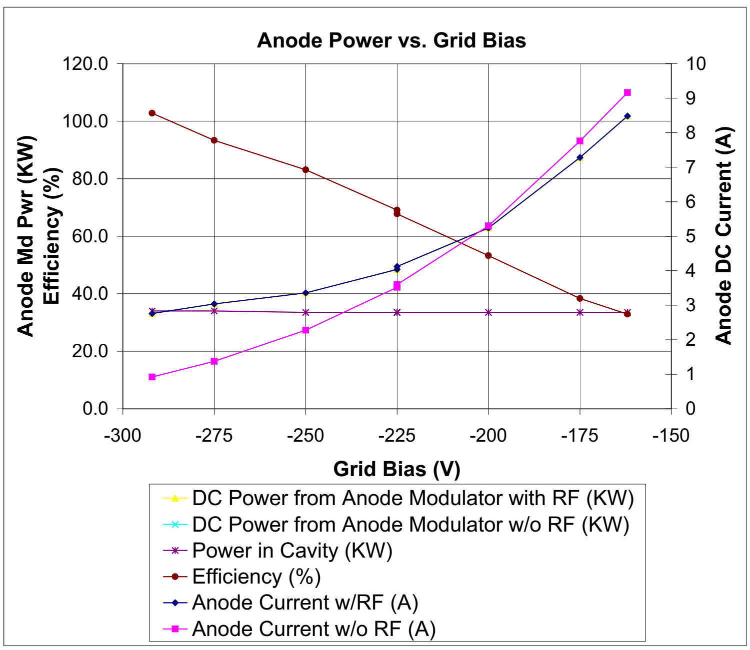
MI Test Station: System Performance vs. Grid Bias @52.814 MHz

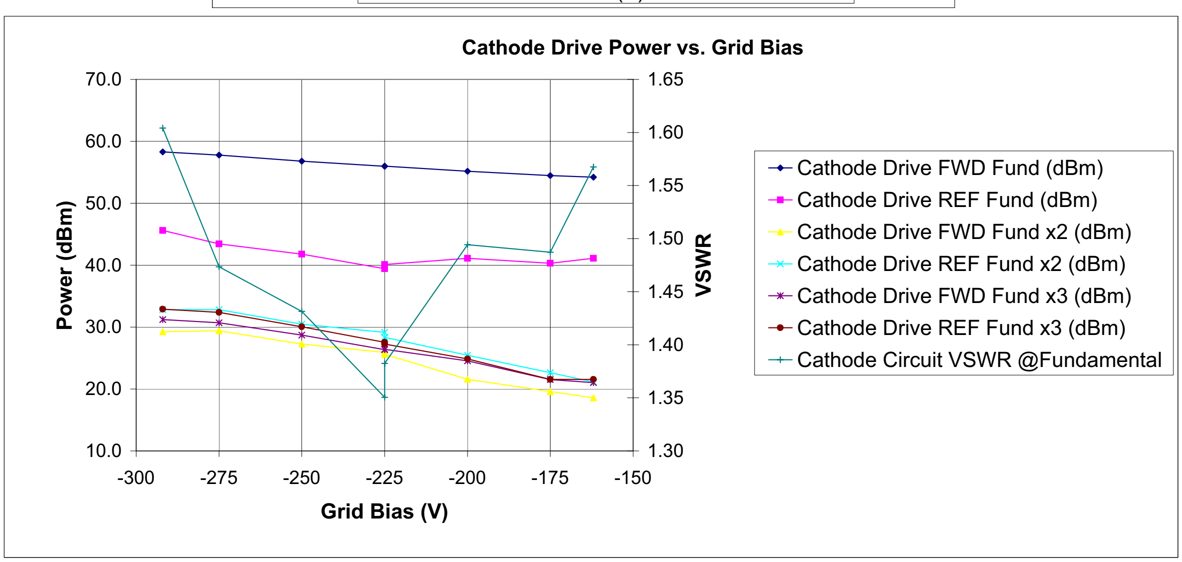
Operating Conditions: Anode Bias = 12 KV

Screen Current Forced to 400 mA



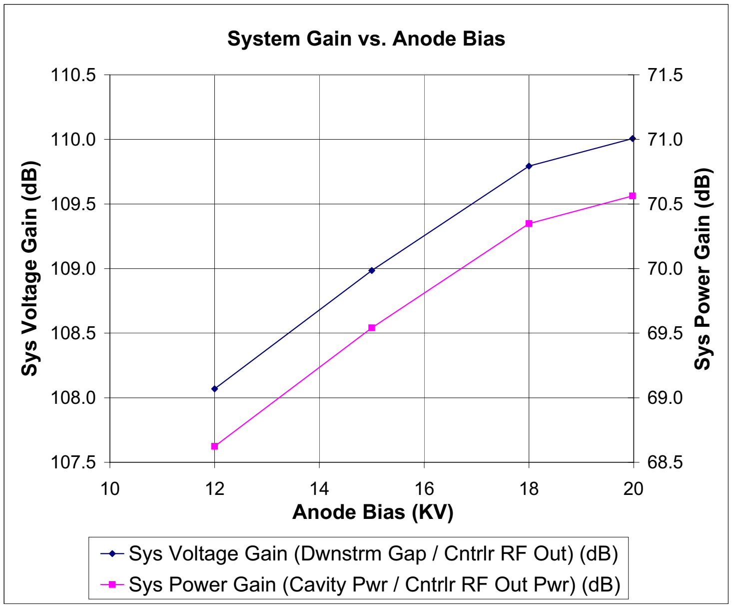


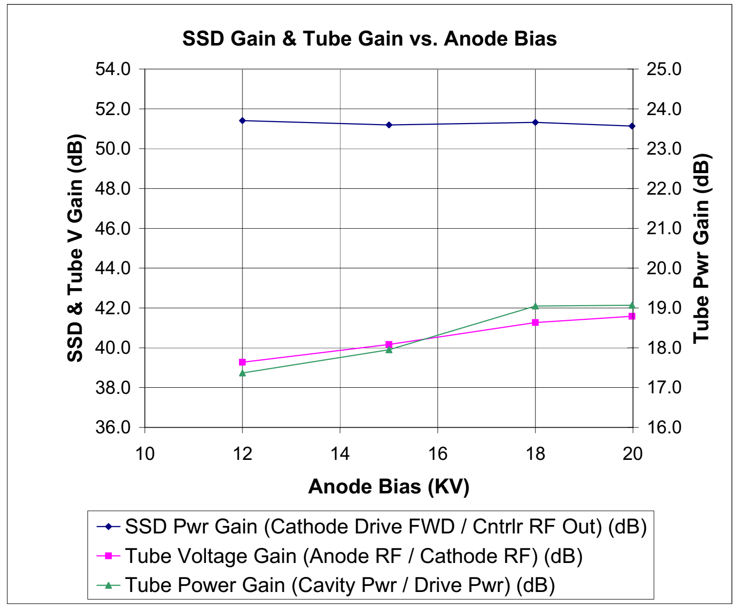


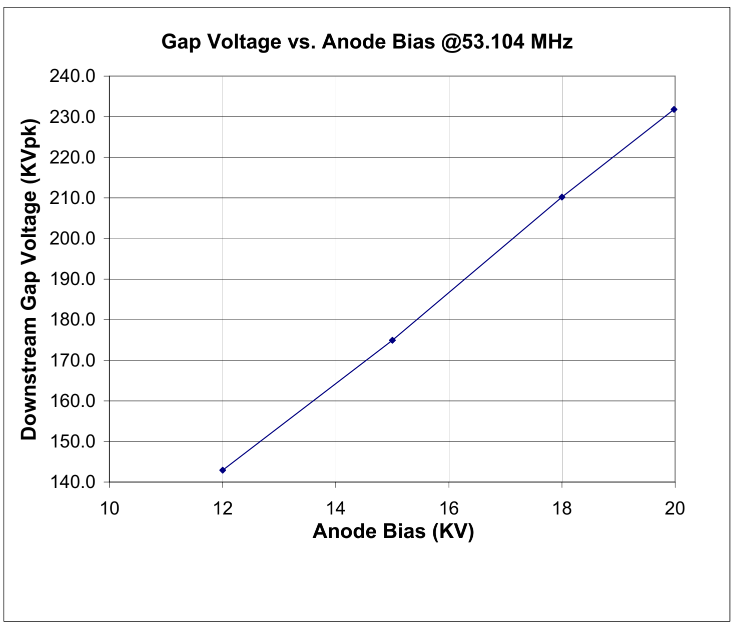


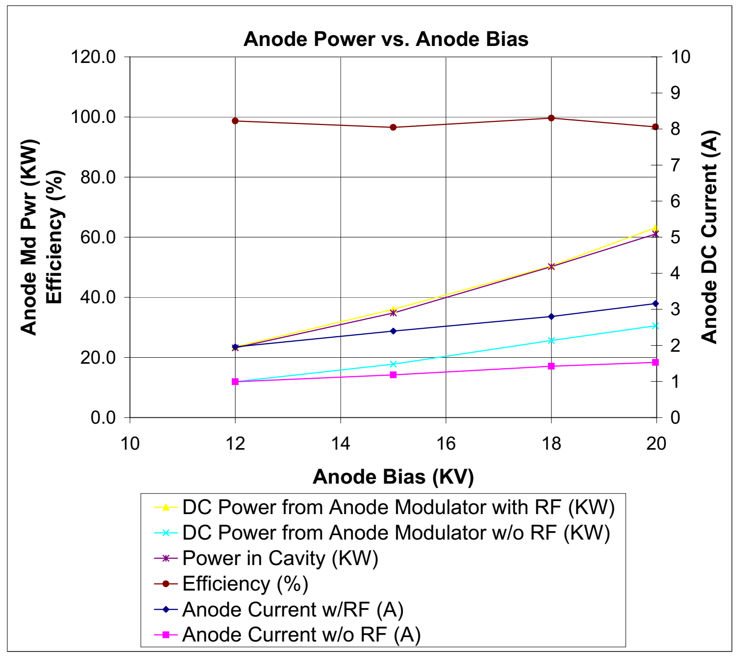
MI Test Station: System Performance vs. Anode Bias @53.104 MHz

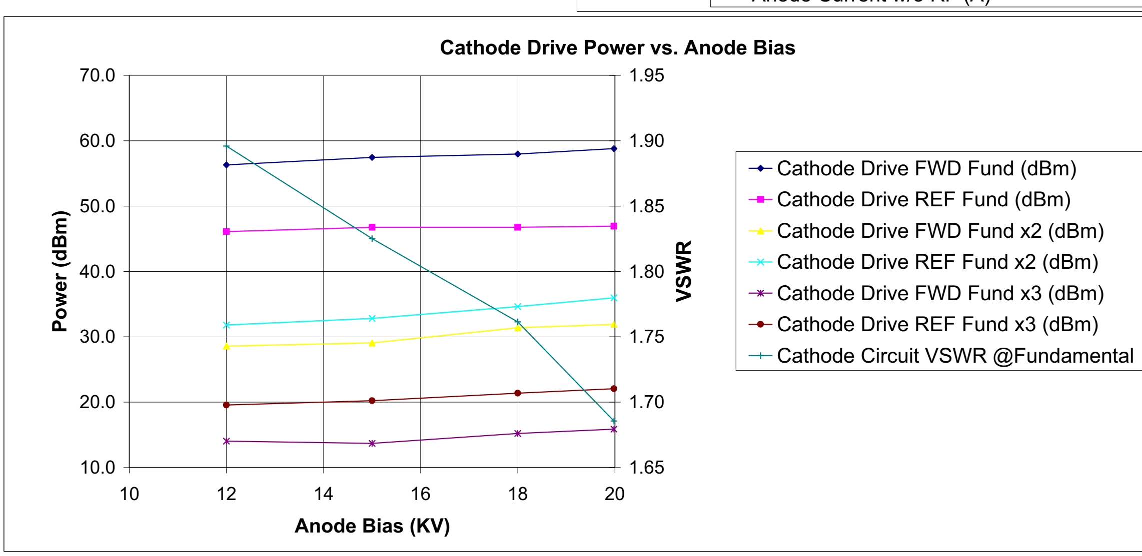
Operating Conditions: Varied the Anode Bias and RF Drive Program w/Screen Current Forced to 400 mA
Grid Bias fixed at -292 V







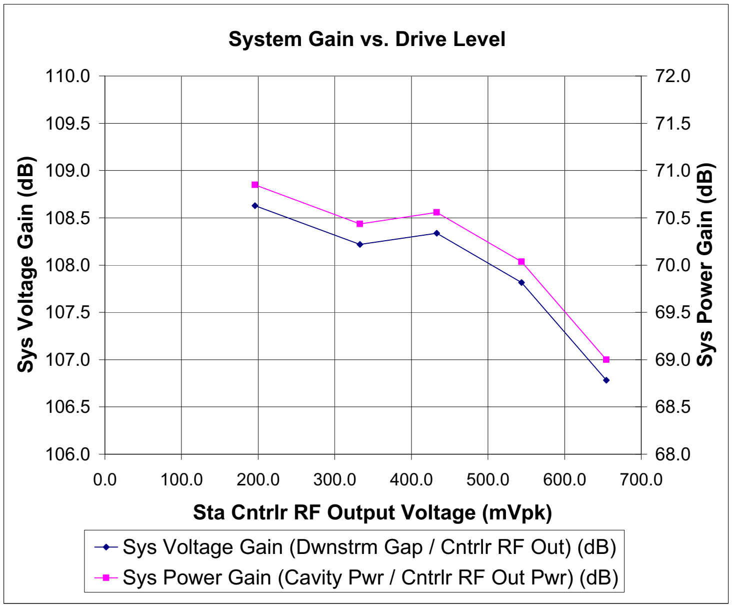


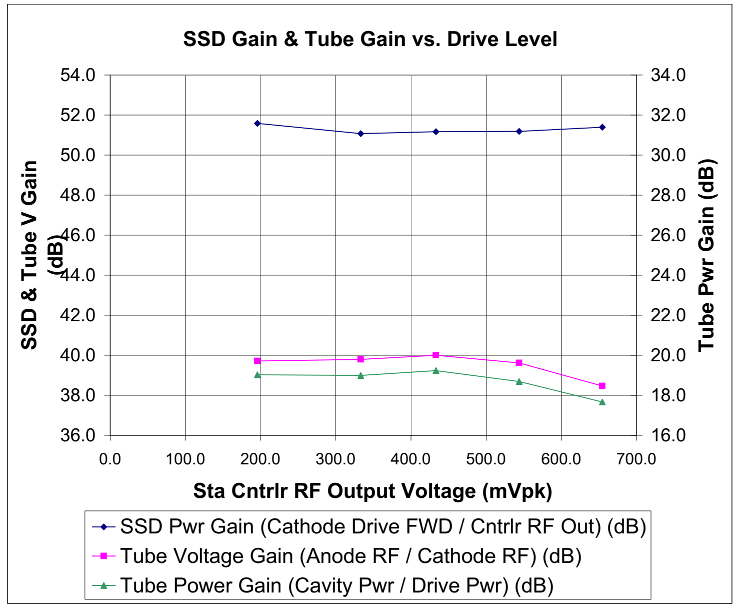


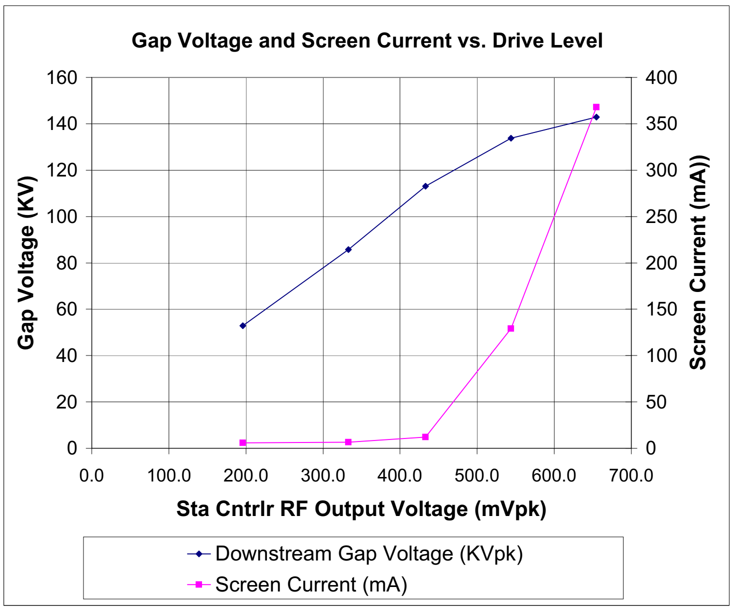
MI Test Station: System Performance vs. Drive Level (No Screen I Reg.) @52.814 MHz

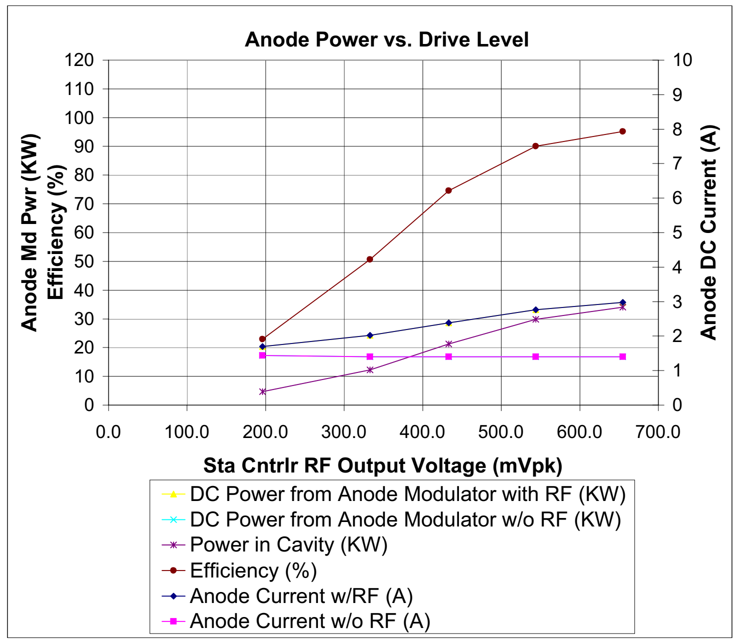
Operating Conditions: Anode Bias = 12 KV, Grid Bias = -275 V

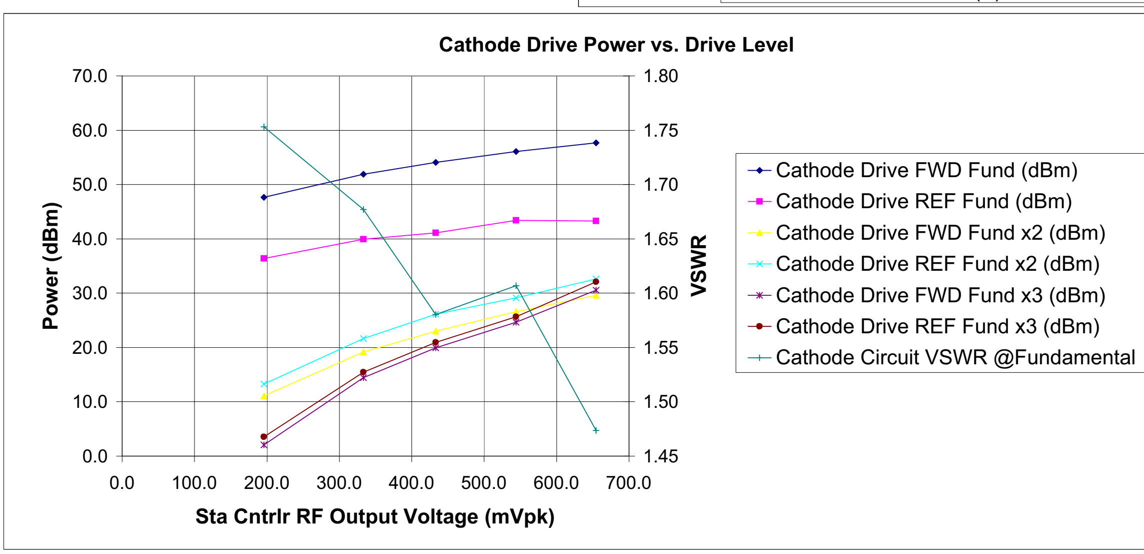
NO Screen Current Regulation







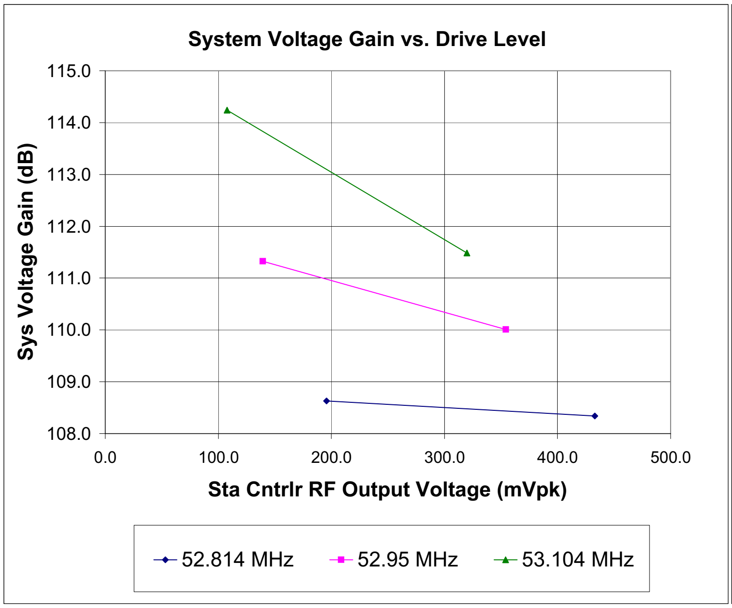


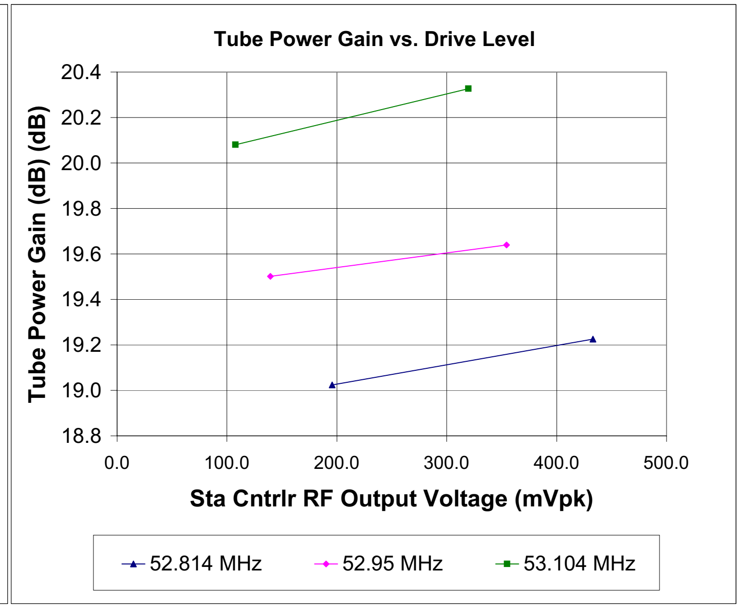


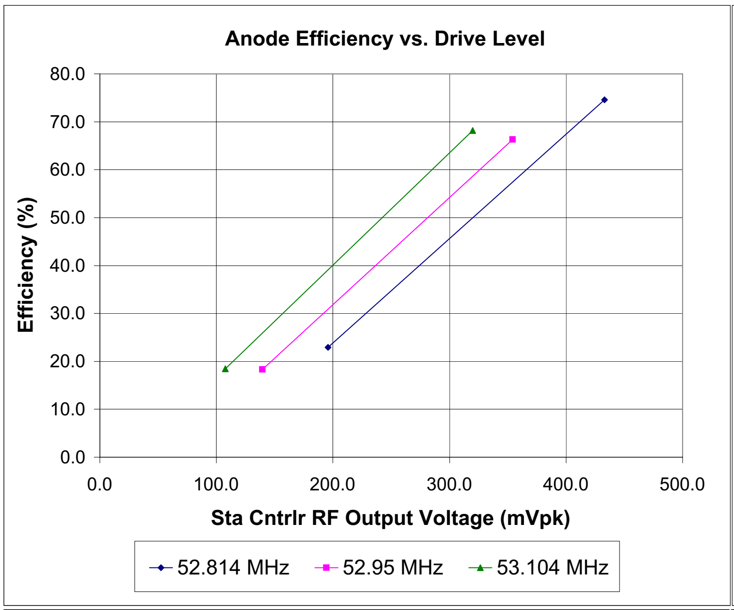
MI Test Station: System Performance vs. Drive Level (No Screen I Reg.) vs. Frequency

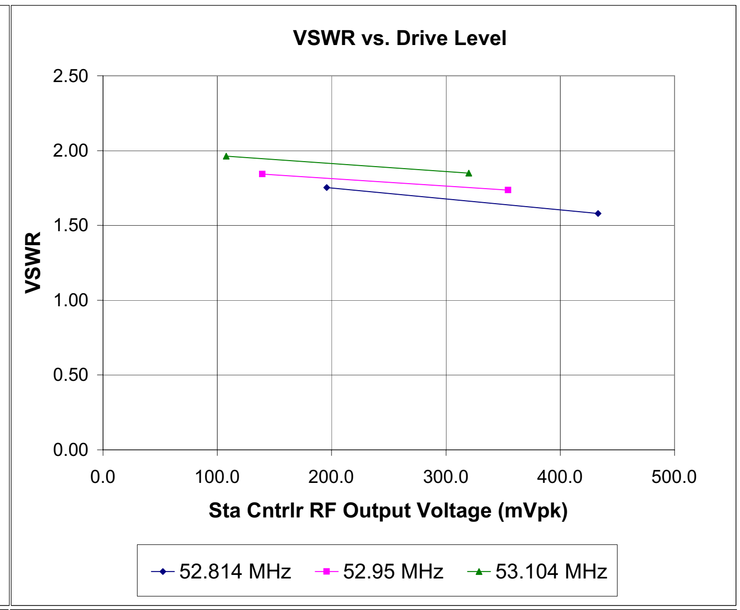
Operating Conditions: Anode Bias = 12 KV, Grid Bias = -275 V

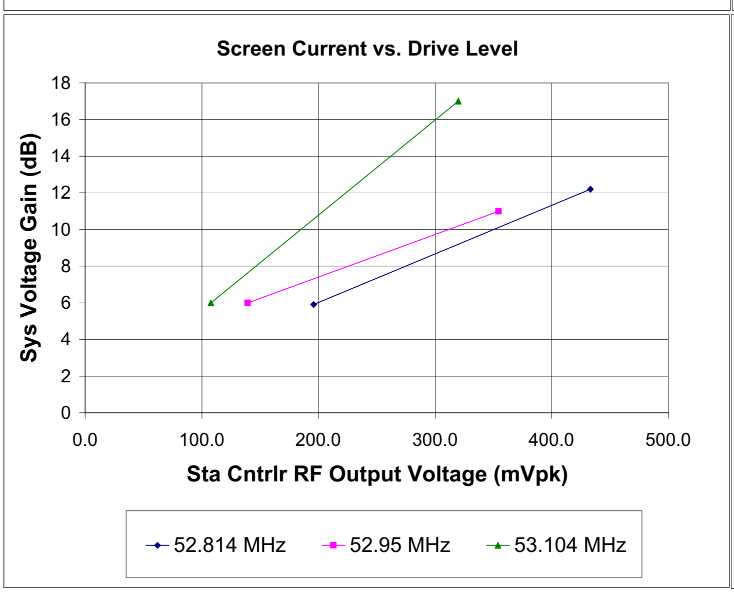
NO Screen Current Regulation

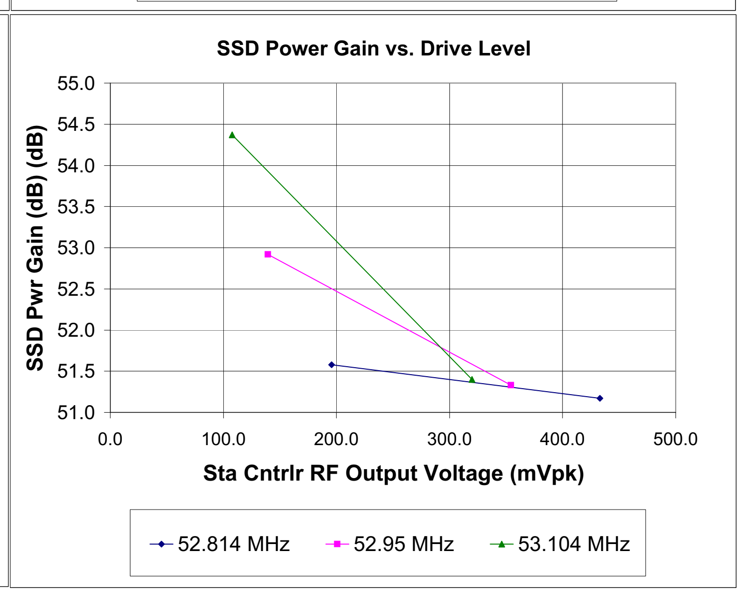












Measurements during Station RF Controller Final Design

Figure 1 can still be used to portray the block diagram of the test setup for measurements made during the final design of the Station RF Controller. The difference here is that all 8 SSD amplifiers were used; thus the true conditions of the final 8 SSD amplifier configuration are considered.

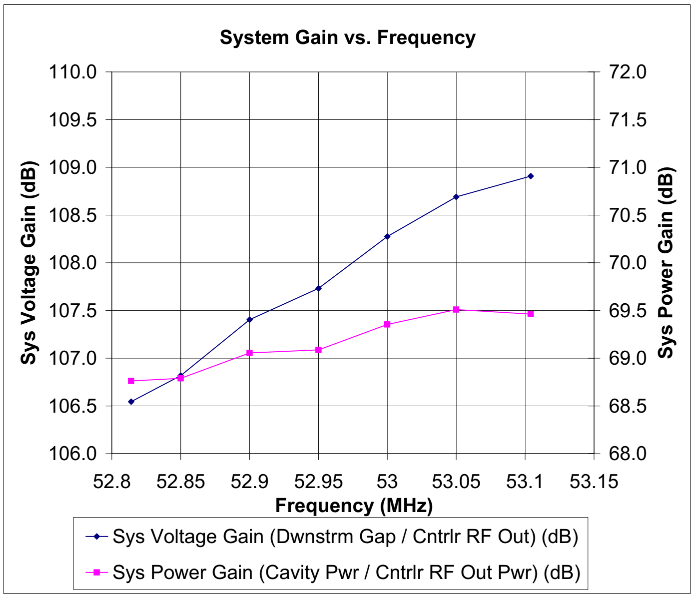
There were 2 variations on these measurements:

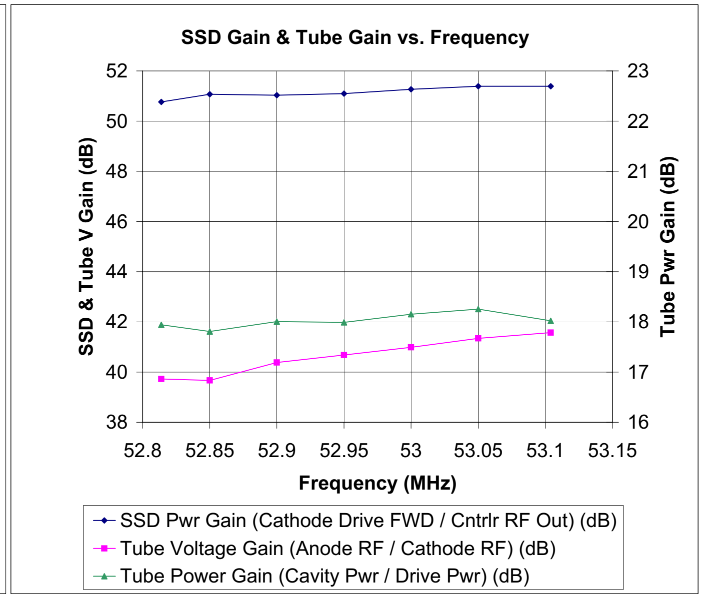
- vs. Frequency
- vs. Grid Bias - note the variation in the cathode circuit VSWR

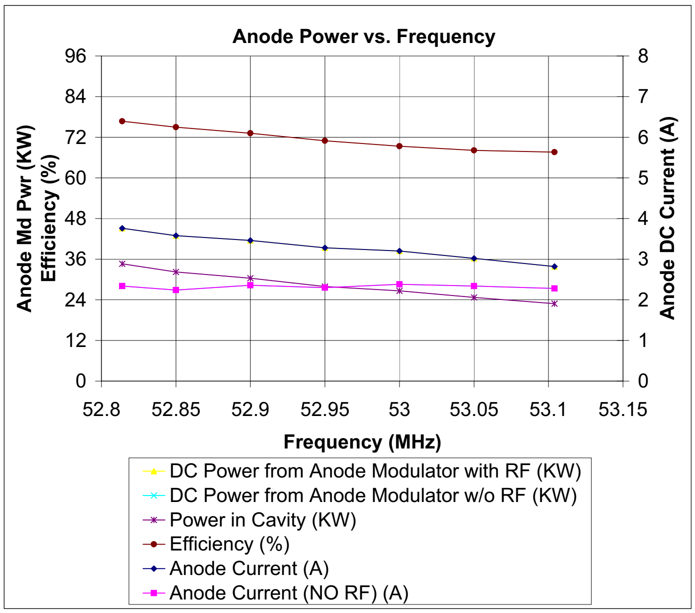
The results of the measurements can be found on the proceeding pages.

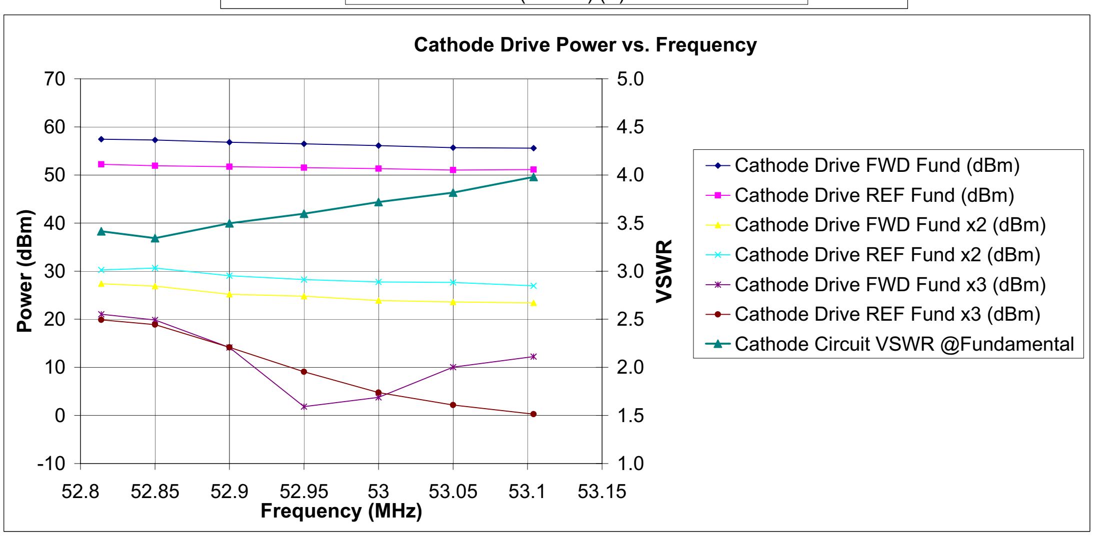
MI Test Station: System Performance vs. Frequency

Operating Conditions: Grid Bias fixed at -275 V, Anode Bias fixed at 12 KV, Screen I at 300 mA





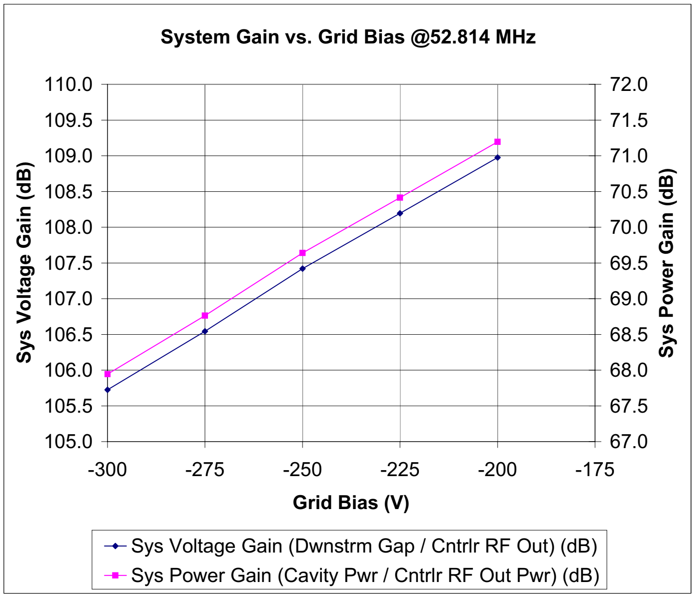


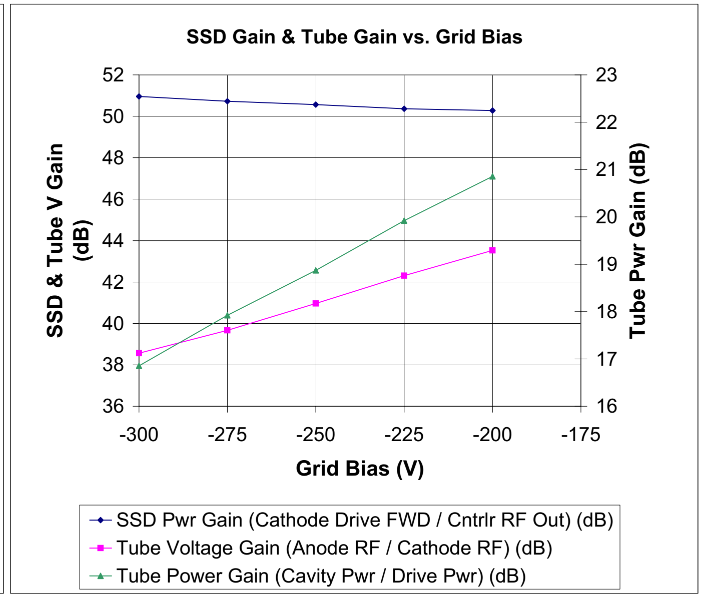


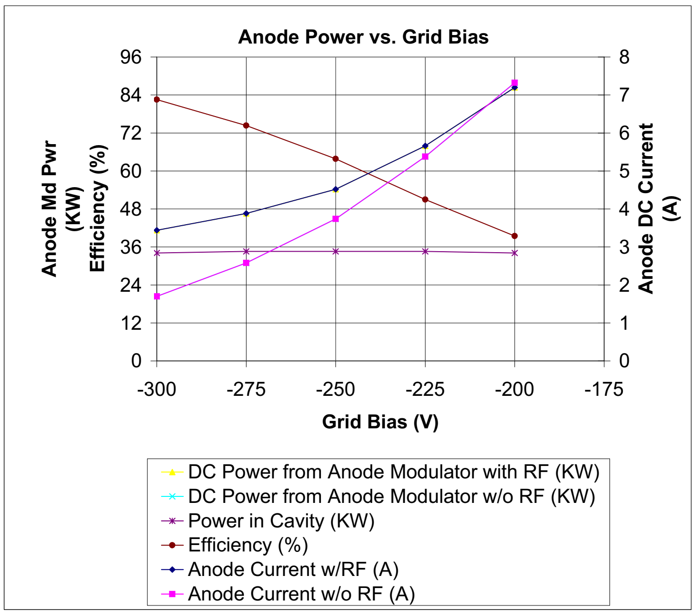
MI Test Station: System Performance vs. Grid Bias @52.814 MHz

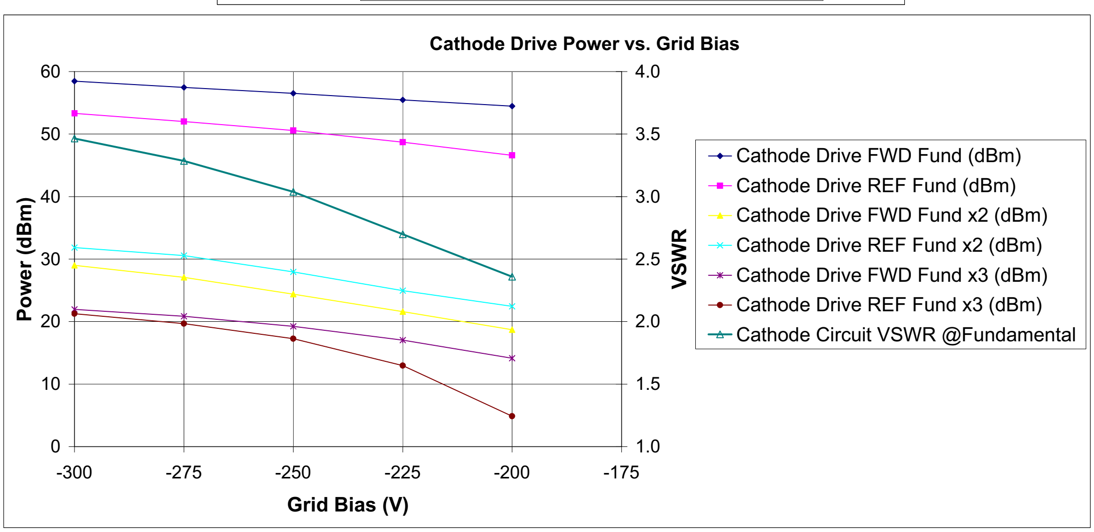
Operating Conditions: Anode Bias = 12 KV

Screen Current Forced to 300 mA









Measurements during MRF Development

Measurements at 52.8114 MHz
Gain vs. Cavity Gap Voltage
(screen current = 200mA, grid bias = -275 V)

Cavity Gap Voltage (KV)	Anode Bias Voltage (KV)	RF Output (Vpk)	System Gain (dB)
20	2.4	0.232	98.7
30	3.3	0.280	100.6
50	5.1	0.364	102.8
70	6.6	0.439	104.1
90	8.7	0.517	104.8

Note: The RF Output level is before the 8-way splitter inside the Station RF Controller.

Measurements at 52.8114 MHz
Gain vs. Grid Bias
(**cavity gap voltage = 20 KV**, **anode bias = 2.4 KV**)

Grid Bias Voltage (V)	Screen Current (mA)	RF Output (Vpk)	System Gain (dB)
-275	200	0.240	98.4
-250	210	0.185	100.7
-225	275	0.163	101.8
-200	400	0.163	101.8

Note: This data indicates that forcing a fixed amount of screen current will not ensure that the same gap voltage is achieved under different grid bias conditions for the same anode bias.

Measurements at 52.8114 MHz
Gain vs. Anode Bias
(**cavity gap voltage = 20 KV**, **grid bias = –275 V**)

Anode Bias Voltage (KV)	Screen Current (mA)	RF Output (Vpk)	System Gain (dB)
2.4	185	0.234	98.6
2.5	160	0.225	99.0
3.0	15	0.148	102.6
4.0	2	0.137	103.3
5.0	0	0.132	103.6
7.0	0	0.122	104.3
9.0	0	0.115	104.8

Measurements at 53.104 MHz
(screen current = 200mA, grid bias = –275 V)

Cavity Gap Voltage (KV)	Anode Bias Voltage (KV)	RF Output (Vpk)	System Gain (dB)
203.5	18.8	0.338	115.6
220.8	20.3	0.349	116.0

The data of this section indicates that the system gain range can be as much as 17dB; from ~99 dB at 52.8114 MHz, 20 KV gap voltage, -275 V grid bias, 200mA of screen current to ~116 dB at 53.104 MHz, 220.8 KV gap voltage, -275 V grid bias, 200 mA of screen current. The range could even be larger if one biases either the anode or grid higher at 53.104 MHz for 220.8 KV of gap voltage.

Presently in MI operations, the extreme operating points are tabulated below:

Extreme Operating Points
Used in present MI Operations

RFSUM Request (MV)	Cavity Gap Voltage (KV)	Frequency (MHz)	Anode Bias Voltage (KV)	Grid Bias (V)	Tclk Curve
0.6	33.3	52.8114	~3	-275	20
0.18	45.0	52.8114	~4.2	-275 to ~ -200	23, 29
0.55	30.6	53.104	~2.8	-275	2A, 2B
3.7	205.6	53.1	~19	-275	23, 29

Note: the 0.18 MV request is during the 4ON slip-stacking portion of the cycle

Conclusion

The system gain measurements documented here were extremely important for understanding the performance of a typical HLRF station. Many system design issues which benefited from these measurements included:

- Station RF Controller module design and component selection including the design of the Direct RF FB gain range
- System voltage gain for RF Drive and Direct RF FB
- System current gain for RF Feed Forward
- Design of the RFOLG function to compensate for changes in station gain in order to keep the open-loop gain constant over varying operating points.
- System program scaling factors
- Calibration procedures and nominal program adjustment knob settings

A typical HLRF station represents a complex non-linear gain block which has to operate over a large parameter space. By studying this data, modifications to the HLRF system were proposed during the MRF design which helped to linearize the HLRF system's response.

Future measurements can be facilitated using the MRF system to apply time sweeping methods that rapidly vary system parameters.